Deep-UV Excimer Laser Measurements at NIST

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ABSTRACT

The National Institute of Standards and Technology has designed and built two electrically calibrated laser calorimeters as primary standards for absolute energy measurements at the wavelength of 248 nm. Under the sponsorship of SEMATECH, NIST developed the calorimeters to improve measurement of dose energy in excimer laser based microlithography. The calorimeter system can be used to calibrate transfer standards which in turn can be used to calibrate detectors employed for energy measurements of semiconductor wafer exposure. The excimer calorimeter uses a glass filter which functions as a volume absorber that allows collection of nanosecond pulses of laser radiation without suffering damage. The measurement range of the calorimeters is 0.3-25 J, but can be extended to 1 mJ with beamsplitters. Electrical calibration of the calorimeters shows a standard deviation in the calibration factor of less than 0.5% for entire energy range. The total uncertainty of typical power and energy meter calibrations is approximately 2%.

Keywords: beamsplitter, calorimeter, excimer laser, exposure dose, volume absorber

1. INTRODUCTION

Deep-UV pulsed laser radiation has several characteristics which can make accurate power or energy measurements difficult. A device to be used for measuring UV laser power or energy must accommodate electromagnetic energy having (1) potentially high irradiance, (2) nonuniform intensity profiles, and (3) photon energies high enough to cause fluorescence or break chemical bonds.

The National Institute of Standards and Technology has designed and built two calorimeters (QUV-1 and QUV-2) to measure the energy produced by excimer lasers operating at the wavelength of 248 nm. The excimer calorimeters use a glass filter to absorb the laser pulses without suffering damage. The glass filter is mounted in a copper cavity surrounded by a constant temperature environment.

Absorption of the laser energy by the cavity raises the temperature which is sensed with a thermopile, and the resulting voltage data are processed to determine the total energy received. The calorimeters are electrically calibrated and are used as absolute laser energy reference standards. The design of the instruments is based largely on previous NIST Q-series calorimeters.[1]

2. DESIGN OF THE QUV CALORIMETER

The principal objective of the QUV laser calorimeter is to absorb all the incident laser radiation with subsequent conversion of the electromagnetic energy to thermal energy. The resulting temperature change is then used to measure the absorbed optical energy. Each excimer laser calorimeter (Figure 1) consists of an absorbing cavity suspended inside a temperature-controlled jacket which provides a constant (with respect to time) temperature environment. This type of instrument is called an isoperibol calorimeter.
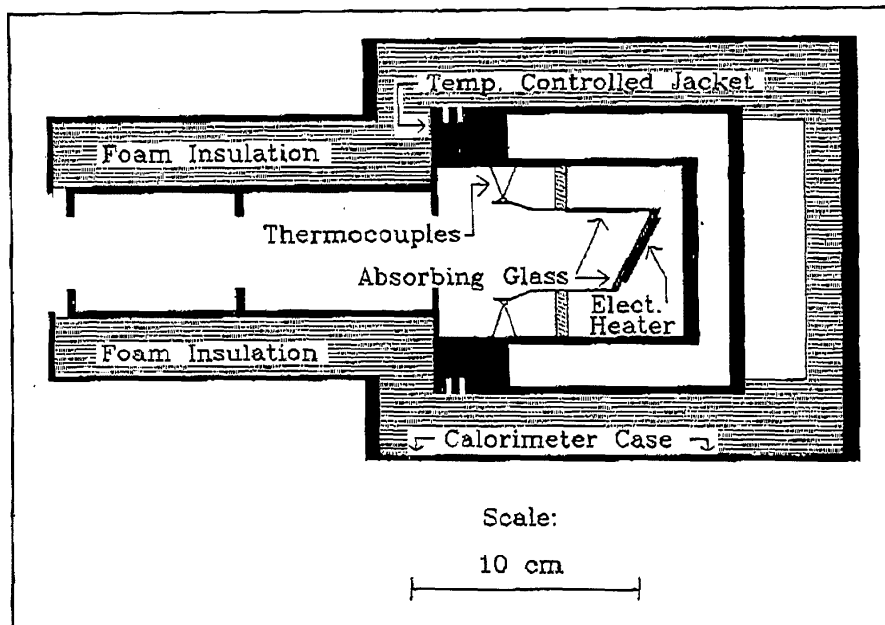

Figure 1. QUV Calorimeter.

2.1 Absorber Cavity

The absorbing cavity is made of thin-walled copper whose outside surface has been gold plated. The laser energy is captured by volume absorbing glass placed at the back of the cavity. The inside surface of the cavity is coated with a flat black paint to absorb any light reflected or scattered from the glass. Because of their design, these instruments are essentially energy storage devices; consequently, the calorimeters have long time constants (approximately 6 minutes).

2.2 Thermopile Sensor

Thermocouples connected in series to form a thermopile are used to measure the temperature difference between the absorbing cavity and the constant-temperature jacket. The thermopile consists of 40 Type E thermocouple junctions. The 20 "hot" junctions are bonded to the gold-plated cavity

surface using a thermally conducting epoxy which has good electrical insulating properties. The 20 "cold" or reference junctions are bonded to the temperature controlled jacket using the same epoxy material. Each junction pair has a temperature sensitivity of about 50 μV/$^\circ$C so the total thermopile has an approximate sensitivity of 1 mV/$^\circ$C. The change in thermoelectric voltage output represents a measure of the amount of absorbed energy. An electrical heater wire is attached in thermal contact to the cavity near the location where the laser radiation is primarily absorbed. This provides the means to calibrate the response of the calorimeter in terms of electrical energy input (Section 5). The calorimeters have been constructed to maximize the equivalence between electrical and laser energy inputs.

The electrical calibration factor for QUV-1 is about 15 J/mV. Therefore, an energy injection of 25 J will produce a maximum estimated temperature change in the cavity of less than 2°C. This small temperature increase is low enough that the thermal coefficients (heat capacity and thermal conductivity) remain relatively constant during the measurement process. Also, the radiative heat transfer is nearly linear for this temperature gradient.

3. ABSORBING-CAVITY STRUCTURE

3.1 Volume Absorber

In order to receive the pulsed-UV laser energy without damage, a volume-absorbing glass filter is used in the cavity instead of black paint or other surface absorbers. The light is changed into heat as the laser radiation propagates into the material volume. As the laser radiation propagates through the glass, the optical power (or energy) density decreases exponentially in the form

$$I(x) = I_0 e^{-\beta x},\qquad\qquad (1)$$

where I_0 is the incident energy intensity, $I(x)$ is the intensity within the material at a distance x normal to the glass surface, and β is the absorption coefficient for the material.

If the energy is absorbed in an appropriate volume of material, the resulting temperature rise at the surface can be held below the damage threshold. For materials with a large β, the energy is absorbed in a shorter distance, allowing a smaller volume of material to be used. However, materials with higher β will also have higher surface temperature for a given laser exposure. Smaller β requires a greater thickness of material for all the energy to be absorbed. A compromise between cavity sensitivity, heat transfer, and damage threshold must be made in selecting the absorber and thickness.

The absorber material selected for the QUV calorimeters was an ionically colored glass.[2] Using transmittance from the manufacturer (and verified by NIST measurements), the absorption coefficient calculated for the colored glass is 3.32 mm^{-1} at 248 nm. Less than 0.15% of the incident energy will be transmitted through a 2 mm thick absorber.

3.2 Absorber Cavity Geometry

As shown in Figure 2, two pieces of filter glass are bonded with thermally conducting epoxy to the back of the cavity structure. The filter glass is thin enough (2 mm) that the laser-generated heat can be conducted into the copper cavity relatively quickly. The piece at the back of the cavity (angled at 60° from horizontal) is 2 mm thick and the piece at the top is 1 mm thick. The incident laser beam first strikes the 2 mm thick glass at a 30° angle of incidence, and most of the radiation is absorbed. The radiation reflected from the front surface of the 2 mm glass then strikes (at 30° angle of incidence) the 1 mm thick glass where most of the remaining radiation is absorbed. The small amount reflected from the front surface of the 1 mm glass strikes the flat black paint coating.
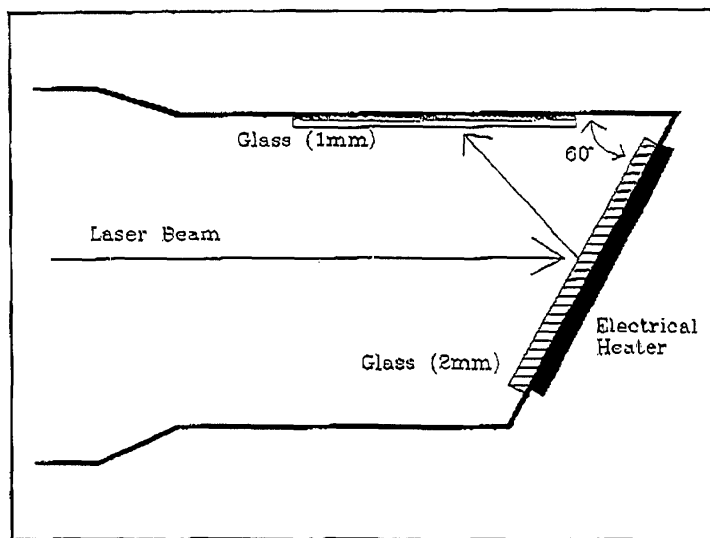

Figure 2. QUV cavity cross section.

3.3 Total Absorption of the Cavity

The refractive index of the absorber was determined by performing a curve fit to a Sellmeier equation using three data points provided by the glass manufacturer.[3] The resulting curve fit furnishes an index of refraction for the absorber glass (at 248 nm) of 1.62. We applied Fresnel's laws of reflection for dielectric materials at 30° angle of incidence and obtained the front surface reflectance (Table I).

Table I. Front Surface Reflectance for the glass filter at 248 nm (30° Incidence)	
Polarization	Reflectance
Unpolarized	4.94%
Perpendicular	7.86%
Parallel	3.68%

The worst case is radiation linearly polarized in a plane perpendicular to the plane of incidence. In this case 7.86% of the incoming laser beam energy will be reflected from the surface of the 2 mm glass and 7.86% of the remaining beam will be reflected from the 1 mm glass. Accordingly, about 0.6% of the incident beam energy strikes the black paint. Assuming an absorption of 95% for the black paint, only 0.03% of the original laser energy is scattered from the paint. The geometry of the cavity will allow a only a fraction of radiation to scatter out. This same geometry was used on the NIST Q-series calorimeters and measurements on the those instruments confirmed this conclusion.

4. CALORIMETER OUTPUT ANALYSIS

The theory of isoperibol (constant temperature environment) calorimeters[4] predicts that the output can be expressed as an infinite series of exponential terms. We use the voltage output of the thermopile as the output variable, assuming it is linearly related to temperature. At some time t_0 after energy injection, the higher order terms decay away, and the output can be described by a single exponential,

$$[V(t) - V_\infty] = (V_0 - V_\infty) e^{-\alpha(t-t_0)}$$ (2)

where

V_∞ = voltage at an infinite time after energy input ends,
V_0 = voltage at time t_0, and
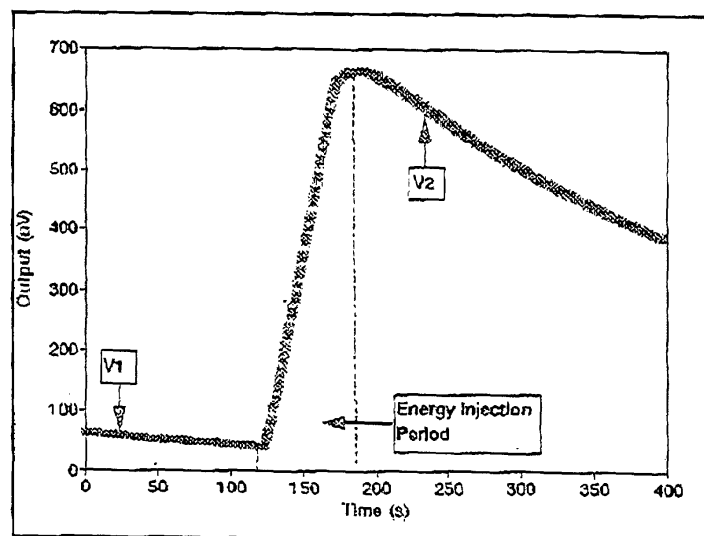α = cooling constant.

Figure 3. Calorimeter Output Voltage.

The voltage output of the thermopile in the calorimeter is sampled and stored with a computer controlled data acquisition system. The resulting voltage-time information must then be processed to determine the dose received by the calorimeter.[5] Figure 3 shows the actual voltage output of a Q-series isoperibol calorimeter during a measurement.

The energy (either electrical or laser) is deposited during the interval labeled "Energy Injection Period." The voltages V_1 and V_2 at times t_1 and t_2 occur long enough after an energy injection that the output is primarily described by a single exponential decay factor. The laser input can be a single pulse or a series of pulses which occur during the energy injection period. The heat flow in the glass absorber and the thermal time constant of the cavity act to thermally integrate the laser pulses allowing a continuous injection of electrical energy to be equivalent to the total energy of the injected laser pulses.

The energy absorbed by the calorimeter is equal to the change in internal energy plus the heat transferred from the system during a measurement. The change in internal energy is proportional to the quantity (V_2-V_1), and the total heat energy transferred is proportional to the quantity

$$\alpha \int_{t_1}^{t_2} [V(t) - V_\infty] dt. \tag{3}$$

Theory predicts that the output of such a device is related to the total energy absorbed by the calorimeter by[4]

$$E = K[(V_2-V_1) + \alpha \int_{t_1}^{t_2} [V(t) - V_\infty] dt], \tag{4}$$

where E is the energy absorbed and K is a proportionality constant. The proportionality constant (calibration factor) is actually a combination of a weighted heat capacity and heat transfer function of the calorimeter cavity structure. The value of K is determined electrically by injecting known energy and then using the voltage curve data to solve Equation (4). The unknown parameters α, V_∞, V_1, and V_2 are found for each measurement run by performing a least-squares curve fit on the voltage data of the calorimeter in the region near V_1 and V_2.

5. ELECTRICAL CALIBRATION RESULTS

Each QUV calorimeter is calibrated electrically by dc substitution. A known electrical energy is dissipated by the heater, and the resulting cavity temperature change is monitored. The thermal power generated in the heater wire is calculated by multiplying the current times the voltage across the heater. The voltage across a standard resistor is used to calculate the current. The total thermal energy is found by multiplying the power by the time during which the electrical energy was injected. The electrical quantities are traceable to highly accurate NIST standards.

The calibration factors for the calorimeter QUV-1 as measured by electrical calibration is 15.23 J/mV and for QUV-2 is 15.87 J/mV. Electrical calibrations have given a standard deviation of less than 0.5% for each calorimeter over the total energy range 0.3-25 J and for injection times from 10 to 180 s. Typically the standard deviation was less than 0.2% at any specific total energy. The value of the calibration factor of each calorimeter is confirmed by periodic electrical calibrations.

6. LASER METER MEASUREMENT AND CALIBRATION

Once the QUV calorimeters have been electrically calibrated they can be used as reference standards to calibrate laser power- or energy-measuring devices. Calibrations frequently require measurements outside the 0.3-25 J energy range of the calorimeters. NIST uses a wedged, multiple reflection beamsplitter to extend the measurement range.[6]

The laser radiation is incident on the wedged beamsplitter where the reflection from the front surface is directed into one detector and the main transmitted beam into the other detector. During a calibration, a standard calorimeter is placed in either beam, depending on the energy requirements.

6.1 Multiple Reflection Beamsplitter

There are two principal advantages to using beamsplitters in laser measurements. If the two detectors used with the beamsplitter both measure energy, then laser stability is not important since they are monitoring the beam at the same time. Also the beamsplitter extends the range of the standard calorimeter by attenuating the beam according to the transmission and reflection properties of the material.

The multiple reflection beamsplitter (Figure 4) is a wedged beamsplitter that has highly polished surfaces and is made of well characterized materials. The relative powers of the emerging beams can be calculated by applying both Snell's and Fresnel's laws of reflection and refraction for dielectric materials. This requires knowledge of the refractive index, the wedge angle, the angle of incidence, and the polarization of the incident laser beam. In the ultraviolet region, fused silica is one of the few materials that can be used for this purpose. It has been thoroughly studied (at visible wavelengths) and the dispersion equation is well documented.[7]
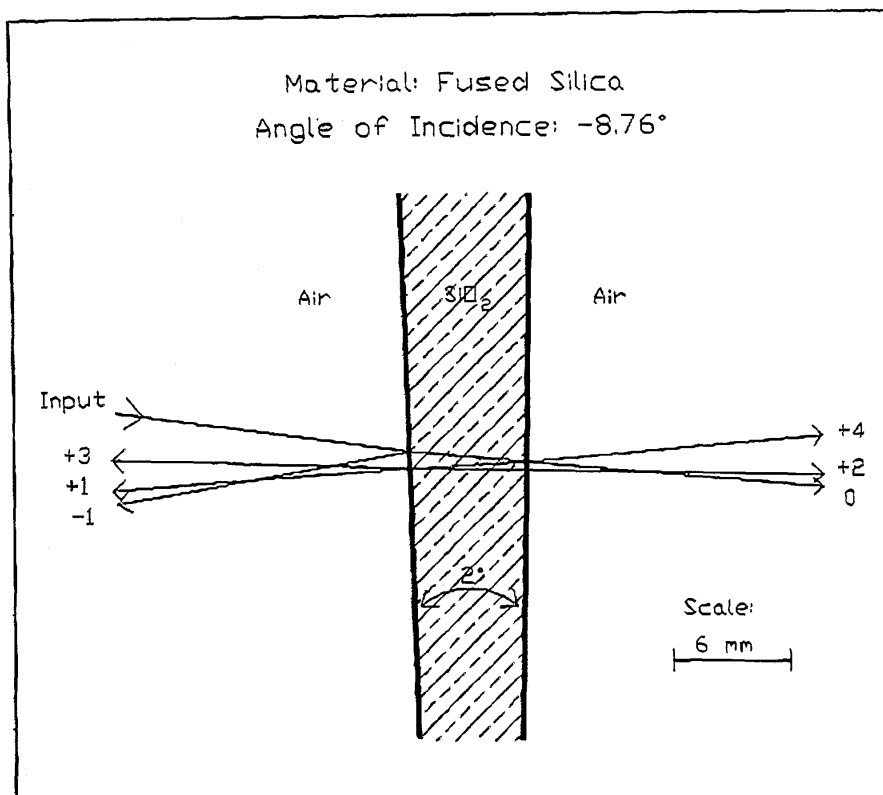
Figure 4. Multiple Reflection Beamsplitter.

The ratio of the power or energy in the transmitted beam to the reflected beam can be confirmed for a particular beamsplitter and wavelength by using the standard calorimeters or two linear detectors to simultaneously measure two beams. A set of ratio measurements is made and then the two detectors are interchanged and the measurements are repeated.[8] It has been particularly important to measure the beamsplitter ratios periodically for the deep UV system because even high purity synthetic fused silica suffers modification of properties under high fluence 248 nm irradiation.[9] Fused silica at a wavelength of 248 nm gives measured attenuation ratios of approximately 25 and 621 with a standard deviation of less than 1.5%.

6.2 Calibration of Laser Power or Energy Meters

The basic system shown in Figure 5 is used to compare laser power or energy meters to a standard calorimeter. A calibration is performed with the standard calorimeter aligned in one beam where it measures the total energy injected. The relative average power or energy in another beam is calculated using the beamsplitter ratio. In the actual NIST measurement system the beam is collimated and spatially filtered before striking the beamsplitter. The beam intensity is not homogenized, thus the intensity profile is spatially nonuniform.
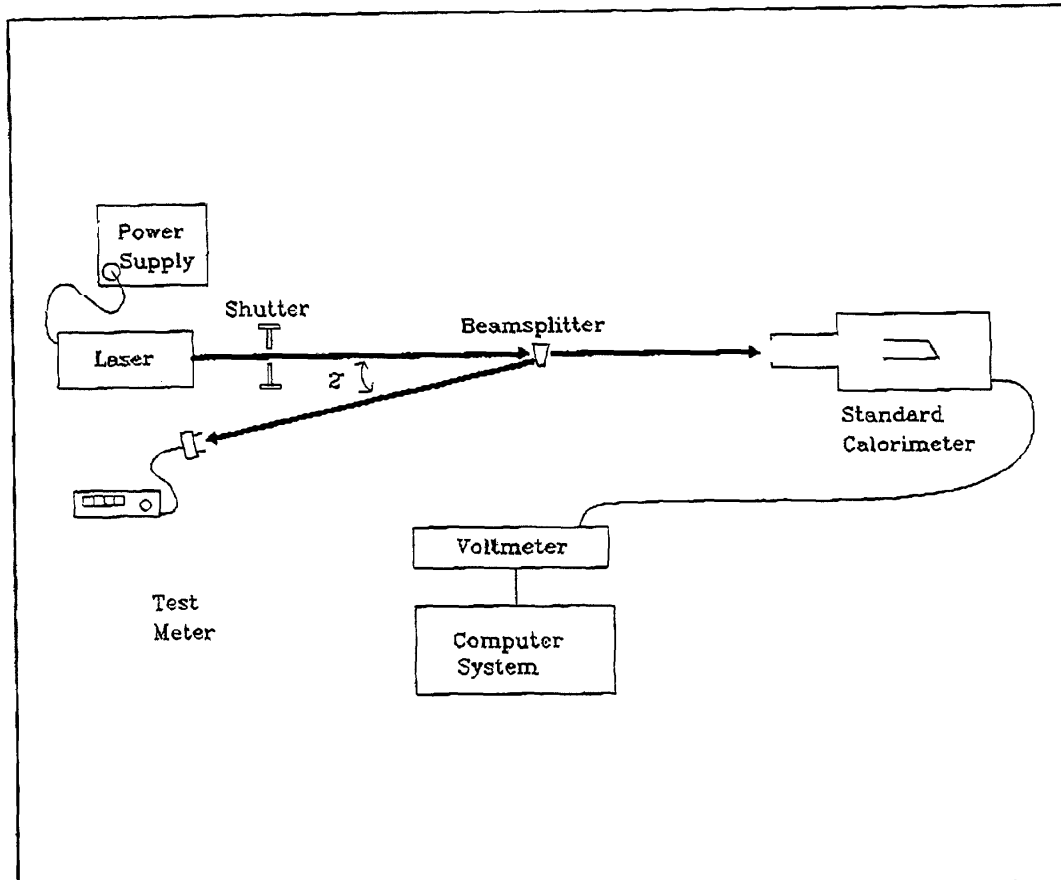
Figure 5. Laser meter measurement system with beamsplitter.

6.3 Calibration System Specifications

The calibration system has the following capabilities in the main transmitted (m = 0) beam.

Wavelength: 248 nm
Pulse Energy @ full open aperture: 100-200 mJ
Beam Diameter: Maximum = 20 mm, Minimum = 5 mm
Maximum Average Power: 20 W
Repetition Rate: 0.5-100 Hz
Pulse Width: 30-35 ns
Fused Silica Beamsplitter Attenuation Ratios: 25, 621

The energy and power range of the system are extended by the beamsplitter. The attenuation ratios are available to reduce the beam energy and allow calibration of meters down to 1 mJ total exposure energy.

7. MEASUREMENT UNCERTAINTY

The total uncertainty associated with a particular laser power or energy measurement is composed of individual uncertainties of the components of the system. The actual uncertainty of each component is unknown; otherwise the result could be correspondingly adjusted to eliminate the error. The total uncertainty for a measurement thus represents an estimate of the maximum uncertainty in the measurement result.

The uncertainty estimate for our laser energy measurements are assessed using NIST guidelines.[10][11] To establish the uncertainty limits, the error sources are separated into Type A, whose magnitudes are obtained statistically from a series of measurements, and Type B, whose magnitudes are determined by subjective judgement, manufacturer's specifications, previous data, and so on. All the Type B uncertainties are assumed to be independent and have rectangular or uniform distributions (that is, each has uniform probability of being within the region and zero probability of being outside that region). The Type A uncertainties are assumed to be independent and normally distributed.

7.1 QUV Uncertainty Assessment

For any NIST measurement, a major concern is the total uncertainty of the primary standard used. The major uncertainty components of these QUV standards are:

(1) Inequivalence: This is the error due to the inequivalence between electrical and laser energy deposition. For a given energy absorbed, the output of the calorimeter may be different for different heat source patterns. The QUV calorimeters are designed to force the heat to flow in a manner which minimizes this inequivalence.

(2) Absorptance: This error is due to radiation which is reflected (or radiated) back out of the cavity. Escaping radiation does not contribute to heating the cavity and, consequently, causes an error in the measurement since it is assumed that all the incident electromagnetic energy stays in the cavity. The cavity geometry and absorbent coatings minimize this error.

(3) Heater leads: During the electrical calibrations, some heat is generated in the wire leads going to the heater coil. This heat causes an error in the calculation of the energy going to the heater.

(4) Electronics: This component is due to the uncertainties in the electronic equipment used. These instruments include digital voltmeters, amplifiers, and timing systems. The uncertainties in the electronic equipment instruments are typically much smaller than the other uncertainty components.

(5) Electrical Calibrations: The calorimeters are calibrated by performing a large number of electrical calibrations to determine an average calibration factor. The scatter of individual measurements about the mean value contributes to an uncertainty in that mean value.

The estimated total uncertainty of the energies measured by the QUV calorimeters is listed in Table II. The individual uncertainty values are based primarily on the Q-series calorimeters uncertainty assessment which are expected to apply to these calorimeters because they are very similar.

Table II. QUV Calorimeter Total Uncertainty	
Error Source	Uncertainty
Inequivalence	0.48%
Absorptance	0.20%
Heater Leads	0.35%
Electronics	0.10%
Electrical Calibrations	0.50% (std dev)
TOTAL	± 0.74%

7.2 Typical Laser Power or Energy Meter Calibration Uncertainties

The total uncertainty for a calibration must include not only the QUV uncertainties but also those from other equipment such as the beamsplitter and the readout device or oscilloscope. Typical power and energy meter calibrations completed thus far have shown a total overall uncertainty of less than 2%. The uncertainty contribution of the readout device is included in the standard deviation of the measurement data.

When a stand-alone detector is calibrated with the output measured by an oscilloscope whose uncertainty is evaluated separately as a Type B assessment, the total uncertainty will be somewhat higher. An oscilloscope with a typical uncertainty around 2-3% will give total calibration uncertainties of 3-4%

8. SUMMARY

Two QUV calorimeters have been constructed, and the calibration system is operational. The QUV calorimeters are intended to be used as reference standards for calibration of power or energy meters used at the excimer laser wavelength of 248 nm. The uncertainties are similar to analogous NIST calibration systems and typically give overall uncertainty of less than 2% for a calibrated meter. NIST is working to improve the deep-UV calibration system and to lower measurement uncertainty.

9. ACKNOWLEDGEMENTS